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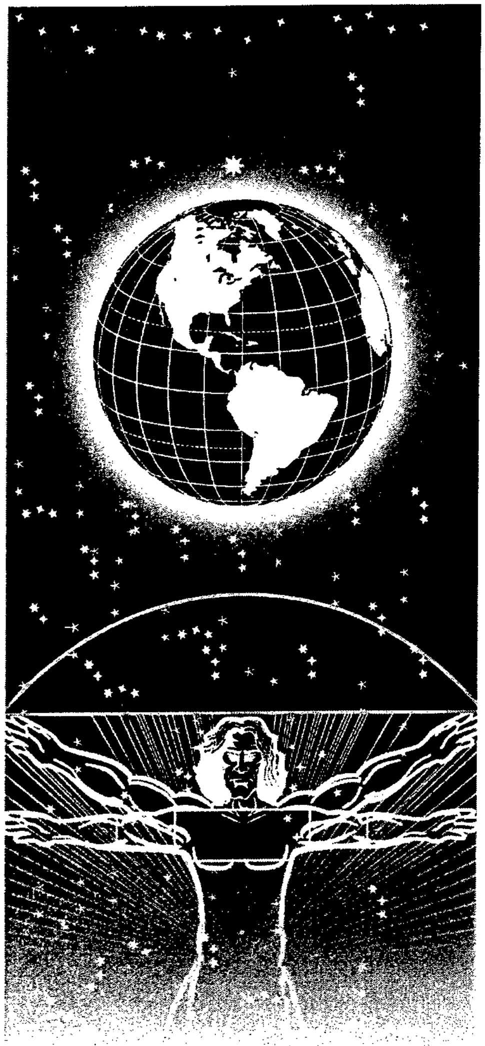

UNITED STATES AIR FORCE RESEARCH LABORATORY

USING THE SIMULATED COCKPIT TO VALIDATE VISUAL PERFORMANCE AFTER PHOTOREFRACTIVE KERATECTOMY IN USAF PERSONNEL

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This report has been reviewed and is approved for publication.

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14. ABSTRACT
In October 1998, the USAF endorsed a longitudinal clinical evaluation of the long-term effects of PRK on visual performance, including three cockpit simulation experiments. Twenty nonflying active duty AF personnel volunteered and were baselined before undergoing PRK at Wilford Hall Medical Center. All three experiments used adaptive threshold estimation to determine visual acuity (VA) and contrast sensitivity (CS) thresholds during various simulated cockpit tasks at baseline, 6-months, 12-months and 24-months post-PRK. Thresholds were determined using both a laser and broadband glare source and a no glare condition. Experiment 1 (Freiburg VA and CS) also used a windscreen experimental manipulation in half of the trial runs. Freiburg VA was almost two full Snellen lines worse with the laser glare source in place versus the broadband glare source, which may be due to masking from coherent spatial noise (laser speckle). Freiburg CS performance dropped significantly following PRK with the no glare condition only. PRK did not affect the ability of the subject to perform Experiment 2 &3 flight tasks.

15. SUBJECT TERMS
Photorefractive Keratectomy (PRK); Ophthalmology; Laser Glare; Broadband Glare; Contrast Sensitivity; Visual Acuity; Cockpit Simulation

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INTRODUCTION

The United States Air Force (USAF) has an ever-increasing number of aircrew members requiring the use of spectacles for flying duties[1, 2, 3]. Spectacle wear can create some significant compatibility issues with the unique life support systems that are essential for survival in the aerospace environment[4]. Soft contact lens (SCL) wear has been approved for aircrew for over a decade to improve life support system compatibility, but not all ametropic aircrew can wear SCLs[5]. Photorefractive keratectomy (PRK) may be another alternative to spectacles and SCLs and may offer some distinct advantages in operational situations.

PRK is a surgical procedure used to correct refractive error in the human eye. An ultraviolet laser is used to modify the optical power of the eye by ablating corneal tissue in selective regions. Removing tissue in the center of the cornea effectively reduces the higher-than-correct optical power of a myopic (near-sighted) eye, whereas hypermetropia (far-sighted) can be ameliorated by removing more tissue at the edge of the cornea and thereby increasing the optical power. Astigmatism (ocular deviation from spherical symmetry) can be corrected through non-uniform ablation of tissue following precise measurement of corneal topography.

Although PRK has been widely accepted clinically, the USAF has concerns about the aeromedical and operational effects of PRK. Other types of refractive surgery, including surgical keratoplasty procedures such as radial keratotomy (RK), have resulted in corneal haze, diurnal refractive instability, excessive ocular glare, and change in prescription following prolonged exposure to altitude[6, 7, 8, 9]. It is possible that PRK could increase a patient's susceptibility to these undesirable conditions. While PRK laser ablation is, in principle, less invasive than RK, PRK is still a surgical manipulation of tissue and therefore initiates a progressive course of injury and healing. The associated tissue transformations can include disruption of the configuration of collagen molecules in the cornea, scar formation, and corneal haze[10]. These conditions might impede vision even in an eye whose refractive error has been corrected perfectly, because they can exacerbate the effects of glare. Glare can be defined as a relatively bright light in the visual field that degrades vision and may cause discomfort as long as the light is in the visual field[11]. Because glare can degrade the retinal image, it can interfere with performance in a variety of visual tasks and conditions. Glare elevates discrimination thresholds throughout the human contrast sensitivity function[12, 13] and can also impede motion perception and the discrimination of objects (including vehicles), particularly at night.

The potential threat from corneal haze and ocular glare may be underestimated or completely overlooked by standard visual acuity tests[14, 15], which still comprise the primary basis for accession and retention in the military. This indicates a need for new tests to evaluate the potential duty impact on USAF personnel. These tests should determine whether PRK could be used to obtain refractive correction without impeding visual processing of static and dynamic stimuli in low-contrast and glare conditions. Since haze and glare effects may evolve over time[16], a meaningful test should accommodate a longitudinal evaluation.

In October 1998, the USAF endorsed a longitudinal clinical evaluation of the long-term effects of PRK on visual performance. This study included five groups of 20 subjects, including a control group and a PRK only group. All 100 subjects underwent detailed visual testing in the Refractive Surgery Center at Brooks AFB, TX. Three groups participated in additional specialized tests representing the effect of different flight conditions on visual function, with a PRK altitude study group, a group that rode the centrifuge to assess G-effects on PRK treated eyes, and a group participating in visual tests in simulated cockpit environments. It is this last study, comprising simulated cockpit experiments performed by 20 volunteer PRK subjects, which we consider in this report. The results of the experiments and visual tests from the other groups will be described in subsequent reports. This simulated cockpit study consisted of three experiments that evaluated different visual tasks in various challenging conditions including both broadband and laser glare.

SUBJECTS

Twenty nonflying active duty USAF personnel (16 male and 4 female) ranging in age from 26 yrs to 47 yrs volunteered for the PRK simulator cockpit studies. The voluntary, informed consent of the subjects used in this research was obtained as required by AFI 40-403. All subjects completed each of the three experiments, to determine a baseline, before undergoing PRK at Wilford Hall Medical Center (WHMC) on Lackland AFB, TX. Data from each experiment were then collected at 6, 12, and 24-months post-PRK intervals. Any post-PRK refractive error was determined prior to each interval, and all subjects wore corrective spectacles, fabricated by the USAF School of Aerospace Medicine's (USAFSAM) Optical Fabrication Laboratory, during data sessions. In order to maintain experimental uniformity, spectacles were included for all subjects, even if they required no correction. The simulated cockpit study was successful in retaining 16 subjects throughout its two-year duration, although only 14 completed all four data collection intervals.

The three experiments in the study all measured visual performance using adaptive threshold estimation, whereby the test adjusts a stimulus parameter (e.g. contrast or target size) across trials to increase the difficulty of the task until the subject's performance deteriorates. Experiment 1 used this principle to determine visual thresholds for acuity

and contrast sensitivity in visually challenging conditions, including glare. Experiment 2 comprised a more operational assessment of acuity using an actual cockpit instrument, the head-up display (HUD). Experiment 3 comprised a dynamic attitude-tracking task, again performed under a variety of visual conditions, including glare.

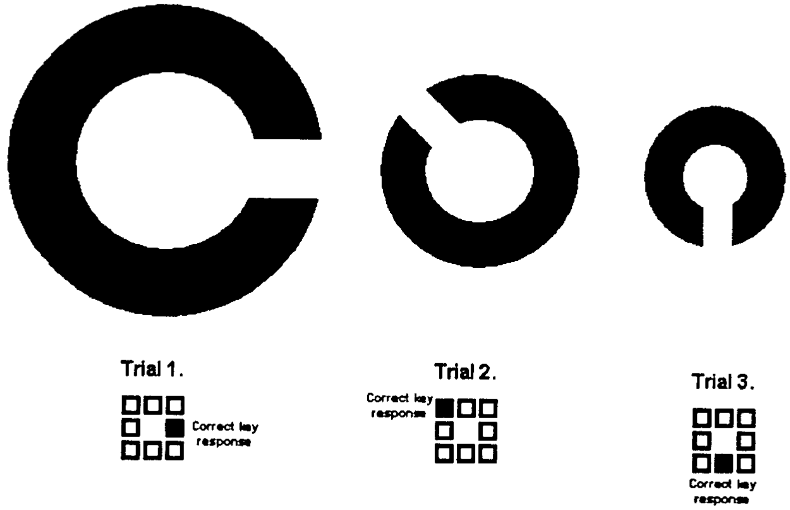
Experiment 1 Methods - Freiburg Acuity and Contrast Sensitivity Tasks Under Various Optical Conditions

The visual stimulus for this experiment was a gapped Landolt ring (a "tumbling C"), presented in a visual performance battery called the Freiburg Acuity Test[17]. In the Freiburg tests, the subject uses a directional keypad to indicate the orientation (eight possible orientations) of the gap in the Landolt target, which is presented as a black or gray symbol on a lighter background. The Freiburg tests include two components, one measuring visual acuity and one measuring contrast sensitivity. Experiment 1 was thus actually two experiments comprising both the acuity and contrast test components. Both tests use Best PEST (Parameter Estimation by Sequential Testing) adaptive threshold estimation to adjust the difficulty of the task across trials according to the subject's performance. In both the acuity and the contrast sensitivity tests, subjects were allowed to respond to each trial at their own pace.

The visual acuity test adjusted the size of the target (and hence the width of the gap) across trials. If the subject responded correctly, the test shrank the target for the next trial, whereas an incorrect response would cause the software to expand the target in the next trial (Figure 1). In this way, the test homed in on the subject's acuity threshold, which was then recorded in decimal form at the end of each test run.

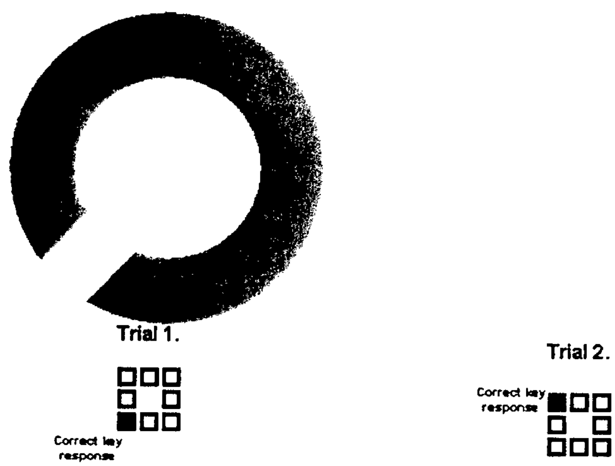
The contrast test estimated the contrast threshold similarly (Figure 2). The diameter of the target was kept constant at 84 arc-min (with a corresponding gap size of 17 arc-min) and its contrast was adjusted across trials by modulating the symbol luminance level. When the subject responded correctly, contrast was reduced in the next trial by increasing the symbol luminance. When the subject responded incorrectly, contrast was increased in the next trial by decreasing the symbol luminance. At the end of the test run, the program recorded the subject's contrast threshold as an inverse Weber ratio. This represents the ratio ($L/\Delta L$) between the background luminance and the luminance difference between the target and background.

The subject viewed the stimuli monocularly from one end of an optical table (Figure 3), and a chin rest anchored the viewing position. Stimuli were displayed on a 21" Radius Precision View color monitor driven by an Apple Power Macintosh G3. The monitor was placed to the side and was viewed in an optical mirror to enable a total viewing distance that would approximate the 20 feet or 6 m typically used in clinical eye lanes to correspond to optical infinity.



Acuity targets will get smaller across trials as you continue to respond correctly.

Figure 1 Visual Stimulus for the Freiburg Visual Acuity Test



Contrast targets will get fainter across trials as you continue to respond correctly.

Figure 2 Visual Stimulus for the Freiburg Contrast Sensitivity Test

Conditions for the Acuity and Contrast Sensitivity Tests in Experiment 1

Test Data. Three experimental variables were included in the design for Experiment 1, namely: date in the subject's longitudinal PRK history; presence and type of glare in the visual field; and presence vs. absence of aircraft canopy ("windshield") material in front of the subject. At each of the four test dates (i.e. pre-PRK, 6, 12, and 24-months), the three (light conditions) x two (windscreen vs. no windscreen) design was conducted for both the left and right eyes, yielding a total of twelve test runs for the acuity test. Another twelve runs were completed for the contrast test on a separate day. The order in which the conditions were presented was counterbalanced across subjects. Each test run comprised 30 trials.

Glare. In the second experimental manipulation, the presence and characteristics of disability glare were varied among three levels. With the no light condition, no glare source was presented. With the laser glare second condition, the Landolt target was surrounded by a ring-shaped, green (532 nm) laser glare source, which was superimposed on the stimulus display using a 60-40 beam-splitter. The beam-splitter was mounted upright, behind the windscreen mounting, at a 45-deg slant relative to the sight line from the viewing position to the mirror in which the display monitor was viewed. The 40% reflection surface of the beam splitter faced the viewer and the remaining 60% of the laser light was transmitted through the splitter to the laser exposure monitoring system. The laser array was created by rear-projecting a diverging laser beam on a diffusing screen mounted to the side of the beam splitter. This yielded a laser glare source comprising an extended green (532-nm) annulus whose inner and outer diameters subtended 3.3 and 4.8 deg, respectively, in the subject's visual field. The mean luminance of the annulus was approximately 6,090 cd/m^2 as viewed in the reflected image with no windscreen. This fell to approximately 4,520 cd/m^2 when the windscreen was added (see description below and Figure 3).

In the broadband condition, a broadband (white) light was used as a glare source and situated behind the beam-splitter (Figure 3). The broadband source was a ring-shaped fluorescent bulb (Stocker & Yale SteadyLite Model 13 Plus) whose inner and outer diameters measured 2-1/4" (5.7 cm) and 3-1/4" (8.3 cm), respectively. Because the inner and outer diameters of the laser annulus were matched to those of the broadband source, the angular dimensions of the two glare sources were closely matched as well. The stimulus was viewed through the annulus and the mounting for the broadband light (Figure 4). The broadband source included an integral power controller, which allowed the experimenter to modulate output luminance throughout a range from 10% to 100%. The emission peak was at 544 nm. The emission spectrum was broad, and included additional peaks at 620 nm (red) and at 440 nm (blue), yielding a metameric white light with a measured color temperature of 5453 K. The laser and white light glare sources were luminance matched (~ 6,090 cd/m^2) with a Photo Research PR650 spectra colorimeter prior to each data session. This fluorescent light source exposed the subjects to a minimal fraction of the threshold limit values[18] for exposure to a broadband source.

Windscreen Material. To enable the testing of the visual performance effects of viewing through an aircraft window (whose scratches, internal diffusion, and imperfections can degrade a visual stimulus' optical quality), a section of polycarbonate windscreen material was positioned directly in front of the viewing position, between the subject and the monitor. The windscreen's mean transmission coefficient was 74.2%. This experimental manipulation was accomplished by including the windscreen in half the trial runs.

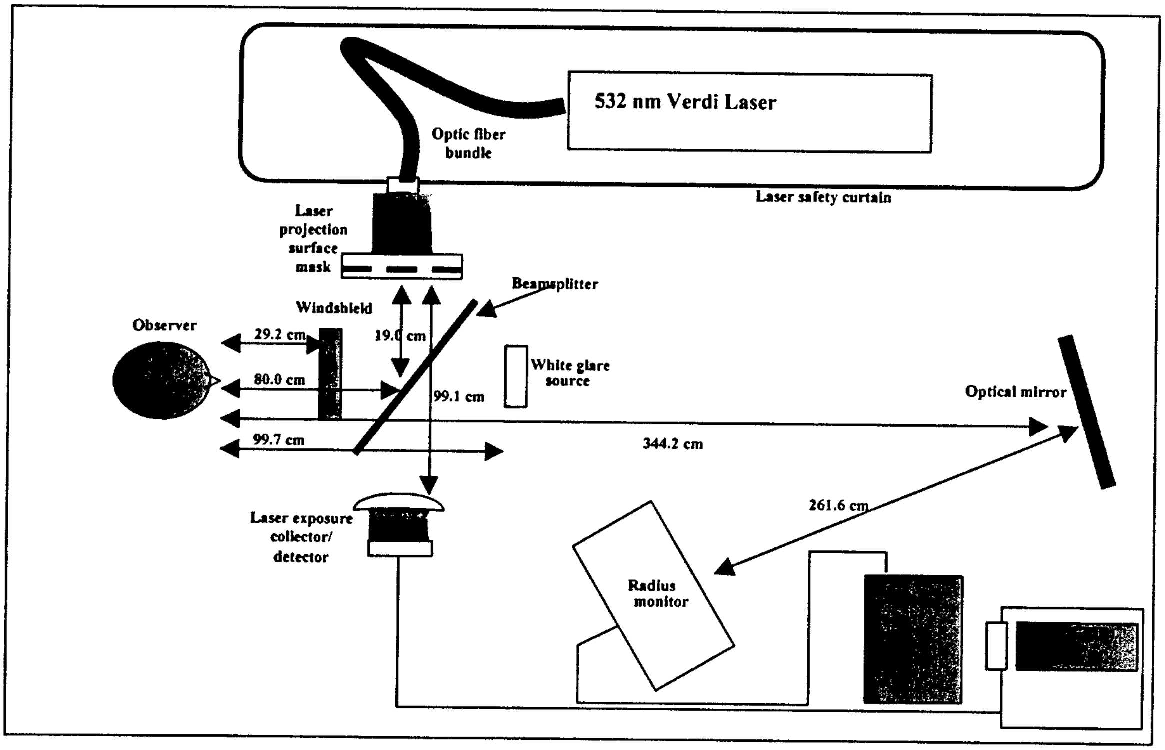


Figure 3. Optical Layout in Experiment 1 (Overhead Schematic View).

Laser System Used in Experiment 1

A 5-Watt COHERENT Verdi laser (Figure 3) was used to produce laser glare for this experiment. The Verdi system is a compact solid-state diode-pumped, frequency-doubled Nd:Vanadate (Nd:YVO_4) laser that provides a single frequency green (532 nm) output. The laser operated at a reduced power (~ 1.5 W) for the experiment, and all safety precautions for a Class 4 laboratory laser[19] were strictly adhered to.

The subject's exposure to laser light was monitored using a collection device comprising a bi-convex lens, a Newport 818-SL detector head, a Newport 4832-C optical meter, and a LabView Virtual Instrument data monitoring application. A 532-nm notch filter (transmission value 48%) was attached to the detector head to restrict the spectrum

of the measured light. This detector head was mounted on the opposite side of the beam splitter from the projection surface on which the annulus was projected, so that it viewed the direct (60%) image transmitted through the splitter instead of the reflected (40%) image seen by the subjects. The lens had an effective diameter of 49 mm and an effective focal length of 38 mm, and was used to steer an image of the laser annulus into the detector. The measured irradiance at the eye for this experiment was approximately .165 $\mu W/cm^2$ with a typical run time of 100 s (16.5 $\mu J/cm^2$). The size and position of the collection device were used to derive correction values from which exposure at the viewing position could be measured and recorded throughout each trial run.[a] Cumulative exposure over the three experiments and the subject exposure log will be discussed after the Discussion Section of Experiment 3.

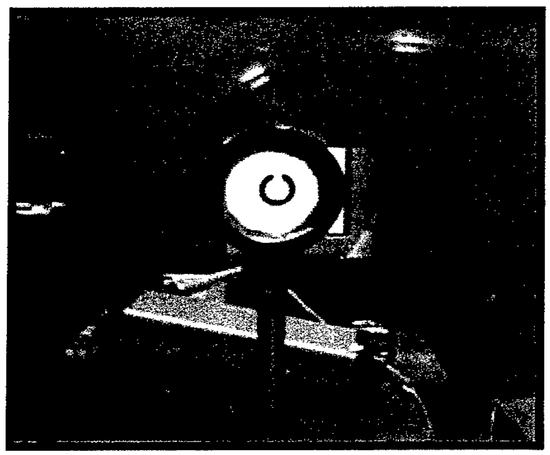


Figure 4. Stimulus Display Viewed Through the White Light Mounting

Experiment 1A Results – Freiburg Visual Acuity Under Various Optical Conditions

Visual acuity data were collected in decimal form and were transformed to LogMAR for experimental analysis[20]. Data were analyzed with a repeated measure 3-way ANOVA with optical glare condition, months post-PRK, and windscreen presence as variables. The main effect for optical glare condition was significant ($p<.0001$), with no-glare conditions yielding lower LogMAR means (superior performance) than broadband glare conditions, which in turn yielded lower LogMAR values than laser glare conditions. The main effect of interposing the windscreen between the subject and the target and glare source was also significant ($p<.0001$), with higher LogMAR means when

[a] Conservative assumptions were adopted wherever possible in the monitoring of laser exposure and the application of correction values. For example, although the glare annulus was large enough to qualify as an extended source, its output was measured in units of irradiance corresponding to the more concentrated power delivery from a point source. In addition, in applying a correction factor to represent the difference between the energy gathered by a human pupil vs. a collection lens 49 mm in diameter; the selected pupil diameter was 7 mm, which is larger (and hence would lead to more exposure) than the pupil of an alert human subject in photopic viewing conditions.

the screen was present. The main effect for months post-PRK did not reach statistical significance ($p=.055$). There were two 2-way interactions that were statistically significant: months post-PRK and optical glare condition ($p<.005$) and optical glare condition and screen ($p<.0002$). The 3-way interaction was not statistically significant.

Several *post-hoc* comparisons were performed to characterize the effects of PRK on acuity in combination with various visual conditions. These comparisons were made using Tukey tests for honest significant differences (Spjotvoll-Stoline Test for adjusted unequal Ns)[21]. Visual acuity (VA) performance was compared between each post-PRK date and the corresponding baseline pre-PRK test for each combination of optical glare (no-glare, laser, broadband) and windscreen (present vs. absent) conditions. With the no glare condition, there were no statistically significant changes in VA whether the screen was in place or not (Figure 5). Under the laser glare condition, there were no significant data collection periods without the screen, but the 6-month post PRK period ($p=.007$) and the 12-month post PRK period ($p=.02$) were statistically significant with the screen in place. The baseline LogMAR visual acuity for the laser condition with the screen in place was 0.29 (20/39 Snellen) while the 6-month and 12-month acuities were both 0.22 (20/33). This represents an improvement in VA at the 6-month and 12-month periods when compared to baseline. The only time period that was statistically significant for the broadband optical glare condition when comparing to baseline was the 24-month post PRK period with the screen in place ($p<.05$). LogMAR visual acuity at this baseline was 0.01 (20/21) while the 24-month post PRK period was 0.07 (20/24), which represents a decrement in visual performance equivalent to 1.5 letters on a Snellen chart.

Since the laser and broadband glare sources were luminance matched and subtended equal visual angles, VA data under the laser optical condition at each data collection period with and without the screen in place were compared with broadband data in the same categories. There was a significant difference ($p=.0002$) between the laser and broadband glare source conditions at every data collection period and with both the screen in place and without the screen. LogMAR VA for the laser glare source condition ranged from 0.15 (20/28) to 0.30 (20/40) while LogMAR VA for the broadband source condition ranged from –0.05 (20/18) to 0.07 (20/24). This relationship is evident looking at the curves in Figure 5 and represents a much better performance on the Freiburg VA task with the broadband glare source in place when compared to the laser glare source.

Since the windscreen had a transmission of 74.2% and most likely scattered light from its surface scratches and imperfections, it was expected that visual performance with the screen present would be degraded when compared to performance without the screen. This was not the case with the no-light condition as there were no statistically significant differences. However, visual performance with laser glare differed significantly between no-screen and screen-included conditions at all four data collection periods, with higher LogMAR values observed when the screen was present [Pre PRK ($p=.0002$), 6-month ($p=.012$), 12-month ($p=.0007$), and 24-month ($p=.0125$)]. LogMAR VA with the screen in place ranged from 0.22 (20/33) to 0.30 (20/40) while LogMAR VA ranged from 0.14 (20/28) to 0.23 (20/34), which represents better visual performance,

without the screen in place. In broadband glare conditions, LogMAR means were higher with the screen present than without in all four data collection periods, but this difference was statistically significant in only one of those periods, namely the 6-month post PRK period (p=.025). The LogMAR VA with the screen in place was 0.02 (20/21) while the LogMAR VA was -0.05 (20/18) without the screen in place.

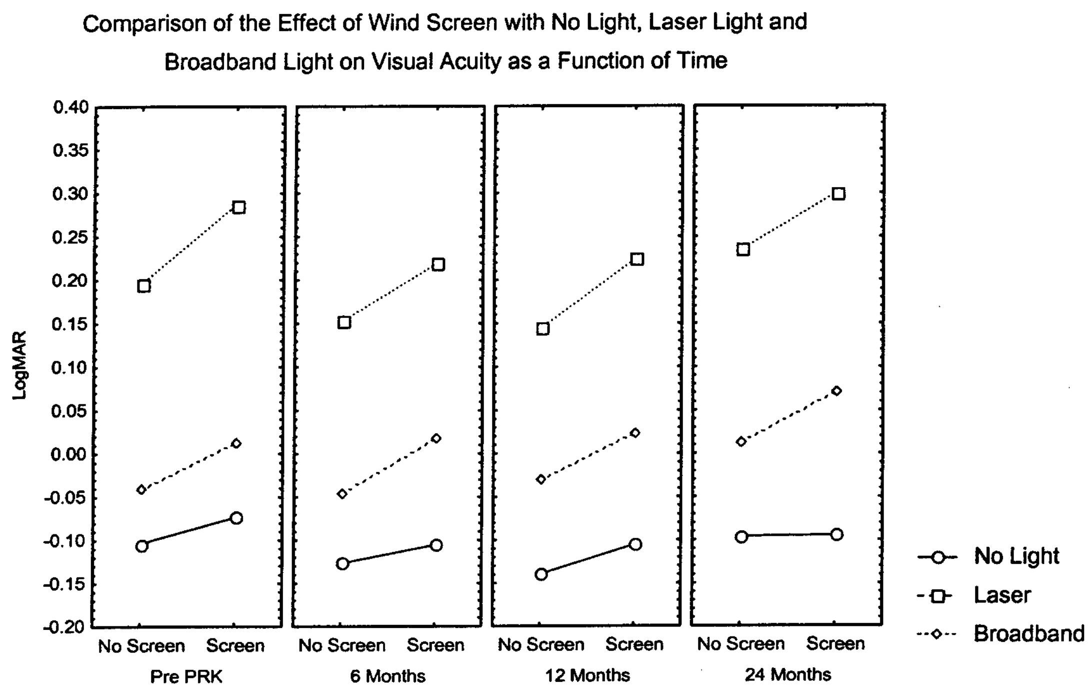


Figure 5 Freiburg Visual Acuity Results

Experiment 1A Discussion – Freiburg Visual Acuity Under Various Optical Conditions

When comparing all the Freiburg VA data under all conditions to their baseline data, there were very few significant results to report. There were two statistically significant improvements to visual performance at the 6-month and 12-month data collection periods for VA with the laser optical glare source and windscreen in place. There have been other reports of improvement of visual performance during these early data collection periods in some of the other AF PRK experiments. However, there were no other improvements of visual performance under any of the other conditions in this experiment including the laser optical condition without the windscreen. Although statistically significant, this improvement of visual performance represents only about one half of a Snellen VA line. The only other statistically significant data period was a decrement in VA at the 24-month data collection period with the broadband glare source

and windscreen in place. This decrement in visual performance represents a loss of less than one half of a Snellen VA line.

During data collection for this experiment, the investigators noted a difference in visual performance in this experiment with the laser glare source in place versus the broadband glare source. This was not an expected finding before the experiment, as both glare sources were matched for luminance, size, and spatial configuration, and this luminance match was verified daily; consequently, it was expected that the mean VAs would be similar. VA with the broadband optical glare source in place was two lines of Snellen VA better than with the laser glare source in place. This difference could be considered operationally relevant. Since the pupillomotor response of a broadband and a visible laser light stimulus are related to apparent brightness[22], pupil size between the two glare conditions should have been similar and not a factor in differing visual performances. The visual performance disparity may best be explained by the optical qualities of the two different glare sources. When looking at the laser glare source, it was obvious that there was some coherent spatial noise (laser speckle), where the broadband source was composed of incoherent light and no speckle. It has been reported that laser speckle has resulted in a significant drop in VA due to spatial masking when using laser created square wave gratings to measure VA[23]. Although the Freiburg stimuli are computer generated Landolt C's and were viewed through the center of the optical glare sources, the laser speckle could have had a surround spatial masking effect on the stimulus that may have reduced the visual performance with the laser glare source in place.

The windscreen degraded VA in this experiment appreciably more with the laser optical glare source in place. The rough surface of the windscreen probably increased the laser speckle and created a more sizeable spatial masking effect. The windscreen also scattered the incoherent light from the broadband optical glare source, but it evidently did not mask the stimulus as profoundly as did the laser speckle. The windscreen did not decrease VA without a glare source in place.

Experiment 1B Results – Freiburg Contrast Sensitivity Under Various Optical Conditions

As with the VA data, a 3-way ANOVA was performed on the contrast sensitivity (CS) data collected in Experiment 1b, with optical glare condition, months post-PRK, and windscreen presence as variables. The analysis was accomplished using the raw (not log-transformed) CS data. The main effects for all three variables were all statistically significant ($p<.0001$), as were the 2-way interaction between months post-PRK and optical glare condition ($p<.0001$) and the 2-way interaction between windscreen presence and optical glare condition ($p<.0005$). The 3-way interaction was also significant ($p=.017$).

As in the previous experiment, several *post-hoc* comparisons were performed to characterize the effects of PRK on CS in combination with various visual conditions. These comparisons were made using Tukey tests for honest significant differences

(Spjotvoll-Stoline Test for adjusted unequal Ns)[21]. CS was compared between each post-PRK date and the corresponding baseline pre-PRK test for each combination of optical glare (no-glare, laser, broadband) and windscreen (present vs. absent) conditions. CS did not differ significantly between the pre-PRK baseline and any of the three post-PRK dates in either of the two optical glare conditions (i.e. laser and broadband). This was observed both with and without aircraft windscreen in place. However, when no glare source was present, CS data in all three post-PRK data collection periods differed significantly (p=.0002) from the pre-PRK baseline data, both with and without the screen in place (Figure 6). The pre-PRK mean CS without the screen in place was 63.05 while the 6, 12 and 24-month post-PRK means were 45.59, 46.76, and 48.39. With the screen in place, the pre-PRK baseline mean CS was 69.83 while the 6, 12, and 24-month post-PRK means were 42.60, 42.16, and 44.33. Obviously, the CS data measured in the no-glare condition in all of the post-PRK data collection periods represent a decrement in visual performance, when compared to pre-PRK baseline.

Again since the laser and broadband optical glare sources were luminance matched daily and they subtended equal visual angles, CS data were compared between the laser and broadband conditions at each data collection period, both with and without the windscreen in place. A statistically significant difference between the glare conditions was observed only in the pre-PRK period without the windscreen in place (p=.015). The mean CS for this laser condition was 8.87 while the mean CS for the broadband condition was 19.64 indicating a better visual performance in the broadband glare condition than in the laser glare condition.

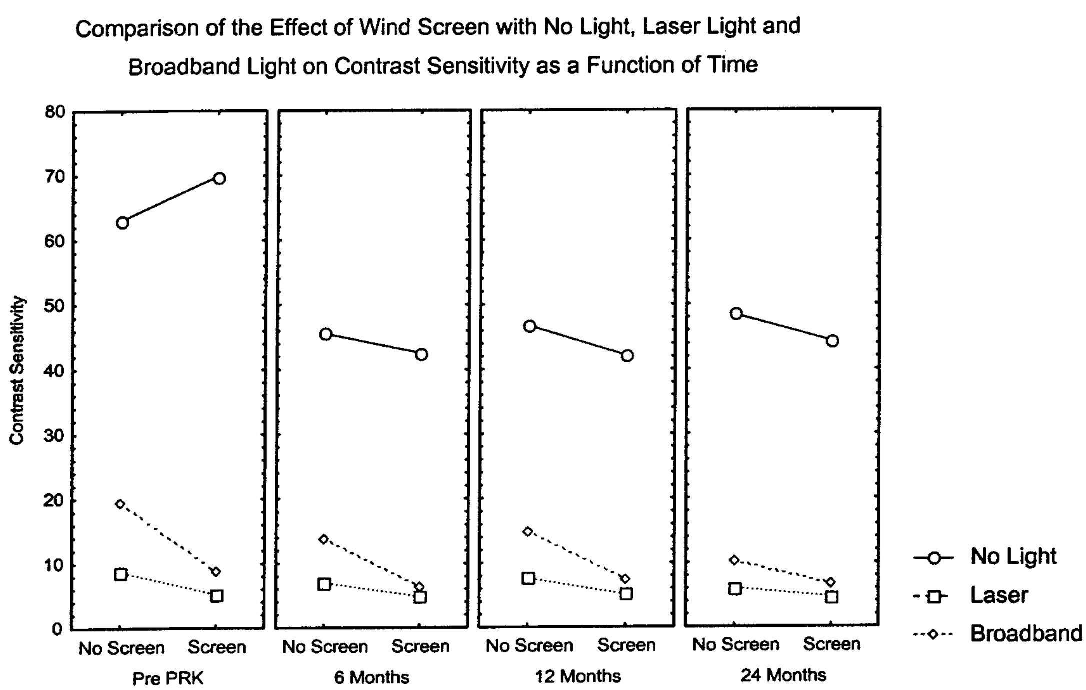


Figure 6 Freiburg Contrast Sensitivity Results

It was expected that the windscreen with its lowered transmission, surface scratches, and imperfections would affect CS, especially with the laser and broadband optical glare sources in place. However, the only statistically significant difference between CS performance with and without the windscreen (Figure 6) was in the presence of broadband glare at the pre-PRK baseline data collection period ($p=.017$). The mean CS without the screen in place was 19.64 while the mean CS with the screen was 8.98.

Experiment 1B Discussion – Freiburg Contrast Sensitivity Under Various Optical Conditions

When comparing all the Freiburg CS data under the broadband or laser optical glare conditions to their baseline data, there was no significant change across the data collection periods. However, the CS means for the baseline pre-PRK data for the no light condition with or without the windscreen were substantially higher than for all of the other data collection periods. The CS means at the 6-month, 12-month, and 24-month data collection periods were very similar which means that after the initial drop off in visual performance after baseline there was no further decrease in CS. This contrasts with the findings in Experiment 1A, where VA was better at the post-op periods, although not statistically significant. The decrease in CS after PRK may indeed be real and a consequence of corneal change post-PRK. However with this sizeable decrease in CS following PRK with no glare source in place, there should have been some parallel drop off of CS performance with the broadband and laser optical glare sources in place. Part of the decrease in CS performance could be an inconsistency in the Freiburg CS data collection program where the CS values on the high end of the continuum may be overestimated. As an example, there were no CS values above 100 for the 6-month data collection period with the no light/with screen condition, but there were six CS values above 100 ranging as high as 151 for the pre PRK no light/with screen condition. These high values may have somewhat skewed the data. However, this can only be a partial explanation as the mean CS values are still considerably higher before PRK than the 6-month values if all values are artificially limited to a 100 maximum. This possible inconsistency in the Freiburg program also does not explain why no subject had a CS value above 100 following PRK.

Since the laser speckle appeared to have a rather profound masking effect on VA in experiment 1A, it was expected that it would have an equal if not more of a masking effect on the CS data[24], and that was the case. However, the broadband glare source also caused a significant decrement in CS performance nearly to the same level as that of the laser glare source. Although CS was always better with the broadband glare source in place versus the laser glare source, the only statistically significant broadband/laser comparison was the pre-PRK data collection period without the screen in place. The broadband glare source may have affected CS performance more than VA performance because of the fixed size (84 arc-min) of the stimulus during the CS phase of the Freiburg experiment. The fixed CS stimulus nearly filled the viewing area through the broadband annulus, whereas the VA stimulus continually decreased in size with correct responses and was always much smaller than the broadband annulus. Thus, there was a lesser amount of broadband surround interference or masking with the VA stimulus then there

was with the CS stimulus. Although CS performance was always worse with the windscreen in place (except the pre-PRK no light condition where overestimation of the CS threshold may have skewed the data), the windscreen did not have the same effect on CS that it did with VA.

Experiment 2 Methods – Reading Symbols on an Aircraft Head-Up Display (HUD) in Various Optical Glare Conditions

Stimuli and Visual Conditions in Experiment 2

Subjects were situated in a model cockpit, which included an F-16 aircraft canopy and a head-up display (HUD) from an FA-18 aircraft (Figure 7). The test was a symbol legibility task in which the subject reported the orientation of the gap with a directional keypad (four possible orientation keys and one no-gap key) in a "tumbling C" target presented on the HUD. The task was made more difficult by the addition of catch trials in which no gap was present. Catch trials were included to reduce the possibility that the subject could merely guess the target's orientation.

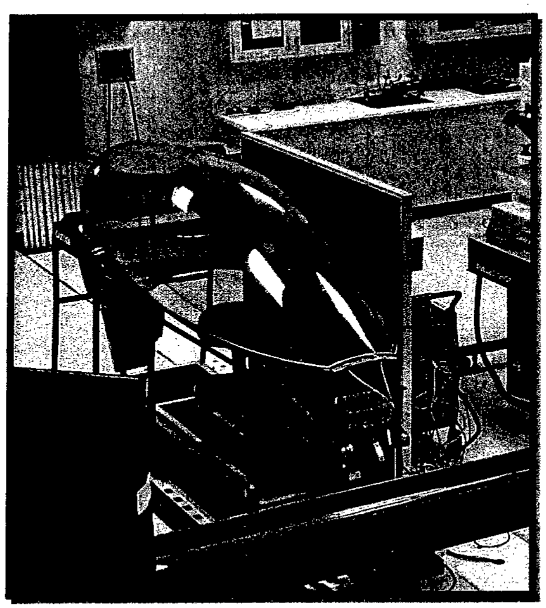


Figure 7. Model Cockpit Including an F-18 Aircraft Canopy

The targets were modified from the traditional Landolt C target in two respects. First, they were drawn in square block form, not in a circular configuration (Figure 8). This configuration was adopted because it was simpler to implement with the available HUD control software. Second, whereas traditional Landolt targets have fixed internal dimension ratios (i.e., the thickness of the ring is always one fifth of its total diameter),

the overall diameter of the targets in this experiment was kept constant throughout all gap widths. This procedure was used in order to measure subjects' ability to discriminate a gap at a fixed eccentricity relative to the center of the glare field. Targets were green with an approximate luminance of 23 cd/m^2 (Minolta photometer) against a dark background.

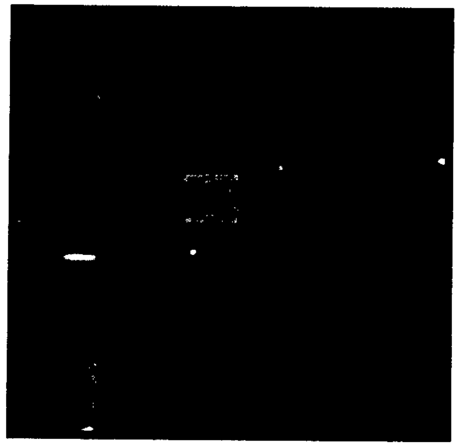


Figure 8 Modified Landolt C Displayed on the FA-18 Aircraft HUD

At the beginning of each trial run, both the height and width of the target measured 100 arc-min, while the target gap (if it was present) and the symbol stroke were both 20 arc-min wide. This initial stimulus configuration mimicked the 5:1 ratio of a traditional Landolt C target. The distance from the center of the target to the middle of the stroke remained constant across trials, at 40 arc-min. The width of the target gap was adjusted across successive trials according to the subject's performance. After each trial in which the subject responded correctly, the stroke width and the width of the gap were reduced by 2.0 arc-min for presentation in the next trial. After each trial in which the subject responded incorrectly, the stroke width and the width of the gap were increased 2.0 arc-min for presentation in the next trial, up to a maximum of 22 arc-min. Within each trial run, each incorrect response was recorded as a threshold inflection or reversal point, as was the next subsequent correct response. Thresholds, in arc-min, were calculated as the mean of the last four reversals. Algorithms were developed to analyze runs with fewer than four reversals, such as ceiling effects (none correct) or floor effects (only one or two misses). In each trial, the stimulus was presented for 500 ms. Test runs typically lasted between ten and twenty trials.

Experiment 2 also had three lighting conditions, including no-glare, broadband, and laser glare. In the broadband glare condition, the glare source was illuminated continuously throughout each trial run. Glare was generated in the broadband condition by placing an annular (ring-shaped) light source in the central visual field as in Experiment 1. Subjects viewed the test stimuli through the ring. The annular bulb was a

Stocker and Yale 973-510 Circle 9 fluorescent bulb whose emission spectrum included line peaks at approximately 440 nm, 550 nm, and 610 nm. Its inner and outer diameters were 5.72 cm and 8.28 cm, respectively, and it was positioned at a 1-m distance, yielding angular diameters of 3.26 deg (.0569 rad) and 4.73 deg (.0826 rad), respectively. Luminance of the source was controlled using a Mercron FX0516 controller, which used an integral photodetector and regulated the intensity of the source via pulse width modulation. The luminance of the broadband source was approximately 16,000 cd/m^2 viewed directly, but was cut to 4350 cd/m^2 when it was viewed through the aircraft canopy and HUD combiner plates. The bulb's measured color temperature was 5119 K. Viewing the broadband source for 300 seconds (five minutes, or longer than most trial runs) was found to produce less than 1% of the Threshold Limit Exposure Value[18].

In the laser condition, the subject was illuminated by the laser prior to the target presentation, and the laser remained on for 5 s during each trial. Glare was generated by projecting a collimated beam from a 2-Watt Millenia (532 nm and operating at 1.5 W) toward the viewing position from directly in front of the aircraft canopy. This laser configuration approximated that of a beam projected onto the aircraft from some distance. The beam source and the center of the HUD were co-located in the subject's visual field. Since both the laser and the HUD were collimated, the visual field configuration would remain uniform throughout minor displacements of the viewer's head. A chin rest and head restraint were used to steady the subject. A photodetector was placed adjacent to the viewing position to calibrate and verify the irradiance reaching the viewer. Output from the detector was measured before and throughout each experimental session using the detector, a Newport light meter, a 532-nm notch filter, and a LabView Virtual Instrument running on a PC. The Virtual Instrument was triggered at the onset of each trial run. The irradiance at the viewing position measured approximately .46 $\mu W/cm^2$ (2.3 $\mu J/cm^2$ for each 5 s trial).

Both eyes were tested monocularly in all three glare conditions. Subjects were tested binocularly as well, completing two trial runs each in the no light and laser conditions. Since the nearby location of the fluorescent broadband source would have created binocular rivalry (due to viewpoint parallax), no binocular test runs were completed in the broadband glare condition. Binocular trial runs were completed twice to obtain a uniform number of observations across the experimental contrast between monocular and binocular viewing.

Experiment 2 Results – Reading Symbols on an Aircraft Head-Up Display (HUD) in Various Optical Glare Conditions

Visual acuity data in this experiment were collected as minimum angle of resolution values and then changed to LogMAR for experimental analysis[20]. Data were analyzed with a repeated measure 2-way ANOVA with optical glare conditions and months post-PRK as variables. Both the optical glare and months post-PRK main effects were significant ($p<.0001$) as was the 2-way interaction effect ($p<.0001$) between them.

The comparisons of interest in this experiment were again how well the subject performed under each optical glare condition over time compared to the performance for that optical condition at baseline. Did PRK have an effect on task performance over time under each optical glare condition? These comparisons were made using Tukey HSD tests (Spjotvoll-Stoline Test for adjusted unequal Ns)[21]. For the no light and broadband glare conditions, there were no statistically significant comparisons for any post-PRK period compared to the baseline (Figure 9). However, for the laser glare condition there was a significant effect ($p<.0001$) at the 12-month post-PRK period as compared to baseline but no other statistically significant effect at either the 6-month or 24-month post-PRK periods. The LogMAR baseline mean for the laser glare condition was 1.30 (20/400 Snellen) and the 12-month mean was 1.0 (20/200) indicating a substantial increase in subject performance at the 12-month post-PRK period when comparing performance at baseline.

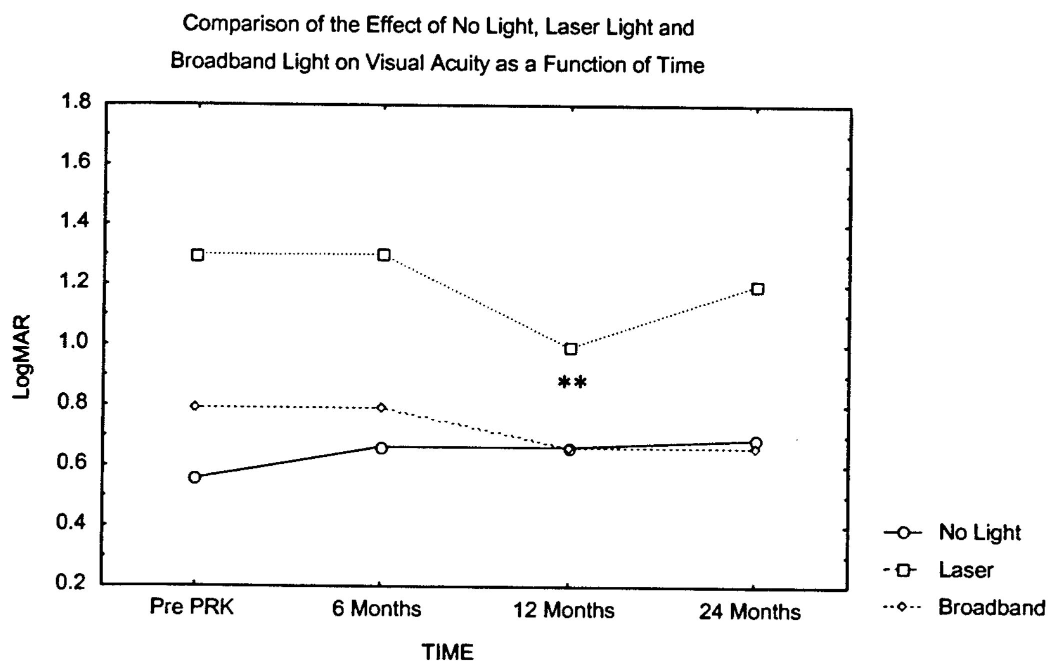


Figure 9 Aircraft HUD Visual Acuity Results
**** represents a statistically significant ($p<.0001$) data point**

Since the laser light source in this experiment was a point source and the broadband source was an extended source, and they were not luminance matched, subject performance between these optical glare conditions should not be compared directly. Baseline means were 1.30 (20/400) for the laser condition versus 0.56 (20/73) for the no light condition and 0.79 (20/123) for the broadband condition (Figure 9). As expected, the visual acuities with the broadband glare condition were higher (poorer performance) than with the no light condition at baseline [0.79 (20/123) vs. 0.56 (20/73)] and 6-months

post PRK [0.79 (20/123) vs. 0.66 (20/91)]. However, acuities were as good or slightly better with the broadband glare condition than with the no light condition at the 12-month [0.66 (20/91) vs. 0.66 (20/91)] and 24-month [0.66 (20/91) vs. 0.69 (20/98)] post-PRK intervals.

Visual acuity means (LogMAR) in this experiment were much higher (indicating worse acuity performance) than would be expected and certainly higher than the Freiburg visual acuity data in Experiment 1A. This was most likely due to the stimulus itself and its presentation; the HUD was not designed as a high-resolution visual diagnostic instrument. The stimulus was not a Landolt C but a modified version (Figure 8) of the Landolt C normally used in visual acuity experiments. The monochromatic stimulus was presented for only 500 ms and was always viewed through the combiner plates of the HUD. The contrast of the stimulus was approximately 77%, and the stimulus was of poor quality on the left side of the Landolt C, which may have confounded the data when the gap was on that side.

Experiment 2 Discussion – Reading Symbols on an Aircraft Head-Up Display (HUD) in Various Optical Glare Conditions

The results of this experiment were rather benign other than the statistically significant ($p<.0001$) data point at the 12-month data collection period under the laser glare source condition. This finding appears to indicate a substantial improvement of visual performance (VA) at that point compared to baseline that warranted investigation to ensure that the data had been collected correctly. Since the data collection periods were months apart and other investigators shared the experimental setup, it was possible that either the laser or the visual stimulus was misaligned. To simulate the experimental setup at the 12-month data collection period, the X/Y offset coordinates of the HUD modified Landolt C stimulus were obtained from the 12-month PRK run files. One of the investigators was then aligned with the stimulus on the HUD in the model cockpit set to those X/Y offset coordinates and the laser was turned on. The investigator reported that the laser did not appear to be centered in the middle of the stimulus as it had been during the other three data collection periods. When verifying the 12-month laser exposure data, the exposures were considerably longer than the other three data collection periods (these exposures were still less than 2% of the MPE). This also would indicate that the task was easier at the 12-month period because of a possible misalignment and the subjects were able to respond correctly for a longer time and down to smaller visual angles. Because of the aforementioned indicators and the fact that VA was not dramatically improved at the 12-month data collection period under the other two optical glare conditions; the best explanation for the 12-month improvement of VA under the laser glare condition is experimental error. On the other hand, VA also improved in Experiment 1A with the laser glare condition at the 12-month data collection period.

There was one other interesting aspect to the data in this experiment. Although VA was better under the no light glare condition when compared to the broadband glare condition at baseline and at the 6-month data collection period, as expected, the mean VAs of the two optical glare conditions were identical at the 12-month period. VA was

actually better with the broadband glare source in place at the 24-month data collection period. One possible explanation for this reversal of the expected outcome is that the presence of the broadband source caused a smaller pupil and a pinhole effect[25], thus improving VA. However if this was the case, the baseline and 6-month data collection periods should also have demonstrated this reversal of expected outcome. Another explanation might be that there was a learning curve with the broadband glare source in place. Nevertheless, there was not a similar learning curve for the no-light glare condition.

Experiment 3 Methods – Performing a Manual Tracking Flight Task on a Synthetic HUD with Various Optical Glare Conditions

Stimuli in Experiment 3

Displays for Experiment 3 were generated in a model cockpit chamber, which housed a Silicon Graphics Crimson workstation with a Reality Engine graphics processor. The display was presented on a Seos Midas collimated system with 1280 x 1024-pixel resolution, viewed in a sound-attenuated chamber.[b] The overall field of view for the display was 44 deg (horizontal) x 27 deg (vertical). A section of windscreen from an A-4 aircraft was suspended in the chamber to provide an operationally relevant optical scattering medium (Figure 10). The distance separating the subject from the windscreen was approximately 19.1 cm. The control interface comprised a joystick and an A-to-D driver. The update rate of the simulator ranged from 16 to 18 frames per sec.

The experiment incorporated an attitude instrument, a simplified rendering of a 1787b HUD attitude indicator as used in the T-38 aircraft (Figure 11). The symbols were drawn on the display using only the green channel, to approximate the hue of actual HUD systems. The peak emission of the green gun was 524 nm. Symbols were drawn on a uniform gray-green twilight background. The instrument comprised a flight path marker, an artificial horizon, and a climb-dive ladder. The artificial horizon subtended approximately 29 deg from side to side, and the climb and dive marker rungs subtended approximately 11.4 deg from side to side. The maximum luminance of the display symbols was approximately 3.3 cd/m^2 but was varied experimentally to determine the functional contrast threshold.

Dynamic Tracking Task, Experiment 3

The experimental task required the subject to maintain a slightly unstable attitude instrument in a level orientation throughout trials that lasted 60 seconds. The bank attitude depicted on the HUD instrument fluctuated over time as if the vehicle were being

[b] The Seos system incorporates a spherical mirror to collimate the image and convey an optical cue of distant focus. This is achieved by mounting the video display monitor in the ceiling of the chamber, facing downward into a beam-splitter. The reflective upper face of the splitter steers the out-the-window display rearward, away from the viewer and toward the spherical mirror. This reflected collimated image then projects forward through the beam splitter towards the viewing position.

buffeted by wind gusts in the roll dimension. The control task was designed after the control model of Kenyon and Kneller[26] where the human observer is the control element in a closed-loop system. The control task also required minor corrections from time to time to correct drift and maintain a level orientation in the pitch dimension. In addition to the unpredictable wind gusts, the task also included a weak instability parameter in the vehicle model. This combination of simulated wind gusts and kinematic instability ensured that a level attitude could not be maintained over time without continual corrections. If the subject neglected the task for a few seconds, the vehicle model would fall into a severe (crash) orientation.

Figure 10 Subject with Joystick Viewing Display Through A-4 Windscreen

In addition to the mild instability, the task was made more difficult by including an adaptive threshold algorithm in the display. This algorithm tested the subject's contrast sensitivity continually by ramping down the luminance of the stimulus over time (while keeping the background luminance constant) until the instrument became faint or disappeared altogether. At this point, the subject's orientation control would falter, and the attitude recorded in the vehicle model would become unacceptably variable, as defined according to the RMS control criterion described below. When this occurred, the display would brighten again rapidly, allowing the subject to regain a level orientation.

Visual performance was assessed by measuring the minimum symbol contrast level the subject could tolerate while still maintaining a level orientation adequately, as defined according to the root-mean-square (RMS) of the roll attitude error. In this context, superior visual performance was indicated if the subject was able to maintain a

low RMS error even when the relative symbol contrast was low. RMS error was evaluated on every frame for the 1.0-second time period immediately previous to that frame. As long as roll RMS remained less than 12 deg, this indicated that the subject was maintaining a level orientation, and the contrast $\Delta L/L$ of the instrument symbols was reduced gradually over time, which made the instrument more difficult to read.[c] As the instrument symbols continued to dim throughout a trial, the subject's attitude control would become more ragged until the RMS criterion was exceeded. The experimental software then eased the difficulty of the task by reversing the luminance ramp, increasing contrast rapidly to restore the visibility of the instrument. Once the subject was again maintaining a level attitude (indicated by an RMS error less than 12 deg), the software would again reverse the luminance ramp and decrease contrast gradually until tracking performance deteriorated. This adaptive cycling of the symbol contrast continued throughout each 60 sec trial and enabled the test to home in on a functional contrast threshold. The performance metric was the mean of all the boundary contrast values at which the reversals occurred across each trial, with lower means indicating the subject's ability to track adequately even in the presence of faint, dim symbols.

The luminance of the instrument symbols was set using normalized display parameters. The background was set to a constant mean luminance of 0.51 cd/m^2. The symbol contrast was varied within a range extending from .001 to 5.0 (again, with better performance indicated by lower relative symbol contrast values). At the maximum contrast level of 5, the symbol luminance was set to a normalized brightness value that yielded a measured luminance of 3.29 cd/m^2.[d] The luminance of the instrument symbols was adjusted across time throughout each trial to add or subtract contrast increments in the Weber ratio

$$C = [L_2 - L_1] / L_1$$

(where L_1 and L_2 represent the background and symbol luminance, respectively) while keeping the background luminance L_1 constant. On the descending (symbol dimming) contrast ramp, the display software reduced C by an increment of .05004 in each frame. On the ascending (symbol brightening) ramp, the display increased C by an increment of .2 in each frame; thus the rate at which the symbol contrast diminished to make the instrument fade was roughly one fourth the rate at which contrast increased to restore the instrument's visibility. The subject's performance in maintaining a level roll attitude (as evidenced by RMS error values less than the criterion value) determined how much time the display remained close to the minimum C value of .001 throughout each trial.

[c] Roll RMS represents the subject's ability to keep the instrument in a stable, level attitude, with lower values indicating better performance. The RMS error criterion was set relatively low, so subjects would not topple far out of control before the display eased the difficulty of the task.

[d] Note that the ratio between this maximum luminance and the specified background luminance of 0.15 ft-L does not correspond exactly to a contrast ratio of 5.0. This resulted from the configuration of the function relating the brightness parameter and the output luminance. The gamma value for the display monitor was selected to make this function as linear as possible, but the function nevertheless exhibited slight non-linearities. While the visual system operates on a log scale (which would tend to minimize the effect of slight nonlinearities), this nonlinearity added variability to the symbol and background luminance values specified by the recorded contrast threshold values.

Visual Conditions in Experiment 3

Like the previous two experiments, this experiment included three visual glare conditions. Each subject performed five 60 s trials under each optical condition. In the no-glare condition, the subject performed the task with no additional light source illuminated near the HUD instrument. In the broadband glare condition, a white annular glare source was used as in Experiments 1 and 2. This glare source was a ring-shaped fluorescent bulb identical to that used in Experiment 1 (i.e. a Stocker & Yale SteadyLite Model 13 Plus). The ring source was mounted facing upward into the lower face of the beam splitter, from which its image reflected back toward the viewing position. The ring was positioned to surround the flight path indicator on the synthetic HUD instrument display. The luminance of this reflected image was approximately 6600 cd/m^2, as viewed through the windscreen material. Unlike the laser source, the broadband light was illuminated continuously throughout all five trials in the broadband glare condition and the inter-trial intervals. The fluorescent source was illuminated continuously to maximize the stability of its luminance output.

In the laser glare condition, the experimental glare source was the end of an optic fiber (numerical aperture = .37) whose image was superimposed on the visual display. The fiber conducted light from the 5-Watt COHERENT Verdi laser to the terminal situated below the display's beam-splitter. The mounting for the fiber terminal placed its image over the flight path indicator on the synthetic HUD instrument. (Although the two glare sources were never presented simultaneously in this experiment, this mounting positioned the fiber terminal in the center of the ring-shaped area occupied by the broadband glare source.) The beam was directed from the laser into the fiber using an optical steering system, which incorporated a power monitor and two Uniblitz T132 shutters. The beam exited the laser and passed through a neutral-density (ND) filter, which was angled to redirect a small percentage of the energy to a photodetector. The photodetector output was delivered to a safety circuit, which would close the second shutter in the event of a surge in power. After passing through the ND filter for the power monitor circuit, the beam passed to the first shutter, which governed the time-course of the laser exposure. An interlock switch was included, which cut power to the laser if the door of the simulation chamber was opened. The path length from the fiber source to the viewing position was approximately 1.0 m. The laser source was illuminated 5 s following the beginning of each trial in the laser glare condition and remained on throughout the remaining 55 s of the trial, yielding a total exposure duration of 275 s across the five laser trials.

As in Experiments 1 and 2, laser eye hazard exposures were monitored during this experiment. A Newport 818-SL photodetector head with a 532-nm notch filter was mounted on the windscreen for stability. A correction factor was entered into the program so that the irradiance at the eye was correctly measured. Output data from this detector were gathered at a sampling rate of 2 Hz, and were integrated using a Newport 1835-C optical meter into a LabView Virtual Instrument running on a laptop. The LabView Virtual Instrument operated continuously and integrated all laser exposure

throughout each subject's five laser exposure trials. The irradiance at the subject's eye measured approximately 1.5 $\mu W/cm^2$, and the cumulative radiant exposure delivered in one 55-s trial was 82.5 $\mu J/cm^2$.

Figure 11 T-38 Attitude Indicator Symbology

Experiment 3 Results - Performing a Manual Tracking Flight Task on a Synthetic HUD with Various Optical Glare Conditions

As described above, the data in this experiment comprise the means (one for each trial) of the boundary contrast values at which the adaptive threshold program reversed the symbol's luminance ramp. These data were analyzed with a Repeated Measures 2-way ANOVA with optical glare conditions and months post-PRK as variables. There was a significant main effect for optical glare condition ($p<.0001$) but the main effect for months post-PRK was not significant. There was a significant 2-way interaction ($p=.02$) between the optical glare condition and the months post-PRK.

Again in this experiment, the comparisons of interest were how well the subject performed under each optical glare condition over time compared to the performance for that optical condition at baseline. In other words, did PRK have an effect on task performance over time under each optical glare condition? These comparisons were made using Tukey HSD tests (Spjotvoll-Stoline Test for adjusted unequal Ns)[21]. For the no light and laser light conditions, there were no statistically significant comparisons for any post-PRK period compared to the baseline (Figure 12). For the broadband glare condition, the 24-month post-PRK results were statistically significant ($p<.05$) when compared to baseline while the 6-month and 12-month post-PRK results were not significant. Since the mean for the 24-month post-PRK period (3.11) was lower than the mean for the baseline (3.44), this represents an improvement in performance at the 24-month period when comparing it to baseline.

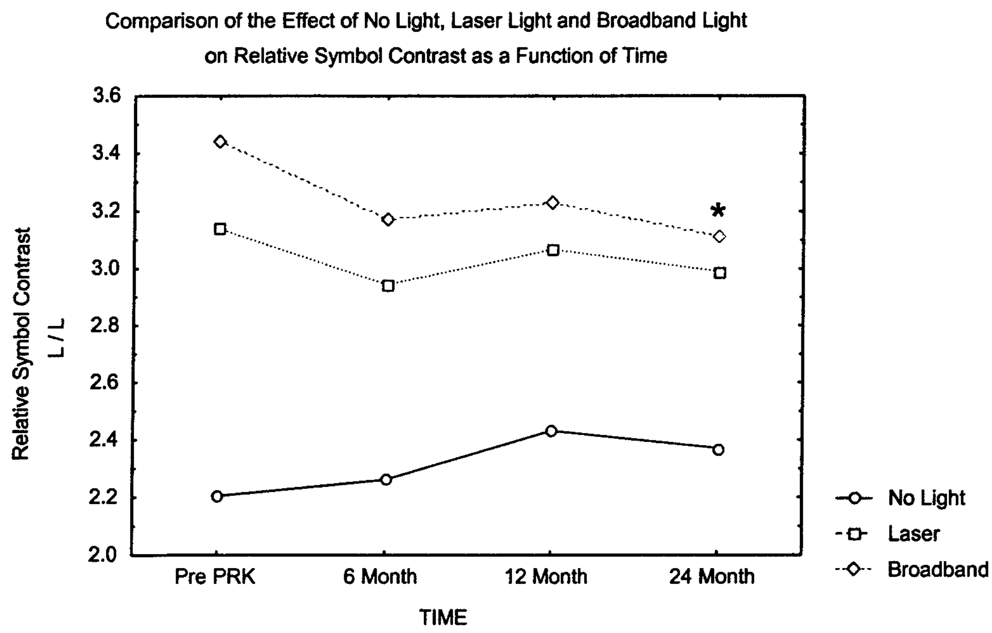


Figure 12 Manual Tracking Flight Task Results
*** represents a statistically significant ($p<.05$) data point**

Experiment 3 Discussion - Performing a Manual Tracking Flight Task on a Synthetic HUD with Various Optical Glare Conditions

The performance task in this experiment was not exclusively a visual task as in the previous three experiments but also incorporated a hand eye coordination element. A recent study on the complex issue of coordination of eye, head, and hand movements suggests that coordination could be sustained only by delaying the hand task until the visual scene had been completely analyzed setting up a temporary, task-specific synergy between the eye and hand[27]. As would be in a potential pilot population, some subjects were more comfortable and skillful using the joystick to guide the changing visual display. In fact, there was a fairly high inter subject variability in performance of this task even after several practice sessions for all the subjects prior to data collection.

Visual performance in Experiment 3 was generally unaltered from the pre PRK baseline except at the 24-month post PRK data collection period with the broadband glare source. This improvement in contrast sensitivity at this specific data collection period could be the result of a "learning curve" in performance of the tracking flight task with the broadband glare source in place. However, there is not a learning curve for either the no light or laser optical glare conditions as the data plots are relatively flat (Figure 12), so the improved performance at the 24-month interval may have been a random finding. It

appears as if PRK did not negatively affect the ability of the subject to perform this particular flight task.

The symbology on the experimental 1787b HUD attitude indicator may not have been sensitive enough to detect any visual performance decrement due to the subtle changes to the cornea that may be present after PRK. Although the performance metric for this experiment was minimum detectable, relative symbol contrast, the experimental paradigm could also be categorized as a line detection threshold task (Figure 11) in the presence of image motion. In the line detection threshold task, the most sensitive band of spatial frequencies shifts toward the lower spatial frequencies as the velocity of visual scene increases[28]. With the broadband and laser optical glare sources in place, this experimental task had to be performed with the peripheral retinas. For a line detection threshold task, the most sensitive bandwidth again shifts to the lower spatial frequencies with increasing eccentricity[29]. Most likely, there would have to have been a significant loss of VA before finding a substantial decrement in task performance. This could be further investigated by comparing the performance of normal subjects on this experimental task to their performance while wearing lenses to artificially lower their VA to various levels (i.e., 20/40, 20/60, etc.).

CUMULATIVE LASER EXPOSURE AND SUBJECT LOG

A cumulative laser exposure spreadsheet was maintained for each subject during each of the four data session periods, i.e., baseline, 6-month post PRK, 1-year post PRK, and 2-year post PRK. The maximum permissible exposure (MPE)[19] for extended viewing for a 532-nm laser is 10 mJ/cm^2 according to the 1993 ANSI standard for safe laser use, which was applied at the time this research was conducted.[e] Each laser exposure during a data session period (one week) was added together and treated as one continuous exposure and then compared to the MPE. The experimental goal was to expose each subject to no more than 40% of the MPE for each data session period. The cumulative exposure totals turned out to be much less than 40% of the continuous exposure MPE. As an example, at the 2-year post-PRK data session period total cumulative exposures for subjects ranged from 4.9% to 6.2% of the MPE.

SUMMARY OF EXPERIMENTAL FINDINGS

1. Freiburg visual acuity (VA) was almost two full Snellen lines worse with the laser glare source in place versus the broadband glare source.

2. The loss of Freiburg VA with the laser glare source in place may be due to masking from coherent spatial noise (laser speckle) surrounding the stimulus.

[e] This standard has since been updated. The new, ANSI 2000 standard specifies exposure guidelines and MPE levels that are similar to, but typically more liberal than, the earlier 1993 standard.

3. The windscreen exacerbated the masking effect of the laser speckle on the Freiburg VA data. The windscreen also had an effect on Freiburg VA with the broadband glare source in place but it was not as noteworthy as the laser source.

4. There was a significant drop off in Freiburg contrast sensitivity (CS) performance with no light source in place at all data collection periods following PRK whether the screen was in place or not. This may be in part due to data skew from the Freiburg CS program overestimating CS values on the high end of the continuum but may represent a true decline of visual performance following PRK.

5. Both the laser and broadband glare sources caused a significant decrement in CS performance versus the no light condition. Although CS was always better with the broadband glare source in place versus the laser optical glare source, the only statistically significant broadband/laser comparison was the pre-PRK data collection period without the screen in place.

6. The results of Experiment 2 were rather benign other than the statistically significant ($p<.0001$) data point at the 12-month data collection period under the laser glare source condition, which represents a substantial improvement in visual performance over baseline. This improvement most likely resulted from misalignment of the stimulus and the laser glare source and may be best explained as experimental error.

7. PRK did not negatively affect the ability of the subject to perform the flight task in Experiment 3. This task was not exclusively a visual task but also incorporated a hand eye coordination element. The symbology in this task may not have been sensitive enough to detect visual performance decrements due to subtle corneal changes following PRK.

8. The methodologies and experimental conditions in these experiments were limited and did not embrace all of the potential visual scenarios that aircrew may encounter following PRK. Therefore, the results should be evaluated in that context and further investigation with other glare sources and visual tasks may be necessary.

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